Balloon Precursor Mission for Venus Surface Sample Return

Viktor V. Kerzhanovich
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
(818) 354-9075 Viktor V. Kerzhanovich@jpl.nasa.gov
Jeffery L. Hall,
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
(818) 354-1531 Jeffery.L.Hall@jpl.nasa.gov
Andre Yavrouian,
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
(818) 354-7544 Andre.A.Yavrouian@jpl.nasa.gov

Abstract – The present scenario of the Venus Sample Return (VSSR) mission [1] includes delivery by a balloon of the Venus Ascent Vehicle (VAV) to an altitude of approximately 60 km where it can be launched without huge penalty for atmospheric losses. The mission includes a number of critical technologies that can be validated in this proposed precursor mission. The other objective of the proposed mission is to collect the more accurate data on Venus atmosphere that is essential for the VSSR mission design.

The mission would consist of an entry vehicle carrying two probes. The entry vehicle would be inserted in the Venus atmosphere from an approach trajectory. One probe will include a zero-pressure balloon that will deploy and inflate at an altitude 55 km and rise to 80 km. During this ascent it will collect data on vertical structure, wind and turbulence that are essential for the VAV guidance and control. These data will be also the first high-resolution data collected for this region of the atmosphere. The data will be transmitted directly to the DSN station.

The second probe will be a sub-scale prototype of the VSSR lander and will include the VAV simulator, the high-temperature balloon, inflation and thermal control systems. During the descent it will provide high-accuracy temperature and pressure measurements of the atmospheric (there is no accurate data on the vertical structure of the lowest 12 km where the Pioneer Venus sensors ceased to operate and the VEGA 2 lander pressure sensor did not have adequate accuracy). The balloon will be inflated and released to ascend to the nominal VAV launch altitude of 60 km. Atmospheric and balloon performance data will be transmitted directly to Earth.
This probe will validate the technologies that are most critical for the VSSR.

As a descope option, the high-temperature balloon could be deployed and inflated at 50-55 km and then allowed to descend to the surface. In this case only balloon technology would be validated.

The paper will discuss the basic mission and system elements.

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1. Introduction

In recent years interest in Venus exploration was overshadowed by spectacular discoveries in the outer planets and an intensive Mars exploration program.

At the same time Venus, being the closest planet to Earth and similar in many respects (mass, size, gravity, dense atmosphere), differs dramatically in others – the most pronounced are high surface temperatures and pressures, super-rotation of the atmosphere, absence of water and sulfuric acid clouds. The study of Venus can yield useful insight into the Earth's behavior, particularly in the area of greenhouse gases and global warming.

Nineteen vehicles have studied Venus atmosphere *in situ*: eleven Venera probes (Veneras 4-14), two VEGA landers, two VEGA balloons and four Pioneer Venus probes. Twelve orbiters/fly-bys gathered remote data: three Mariners (Mariner 2, 5,10), Pioneer Venus orbiter, Magellan, Galileo, four Venera orbiters (Venera 9,10,15,16), and two VEGA vehicles. These data reveal many features of the atmosphere. Veneras 9-12 returned first *in situ* images of the surface of Venus. Orbital radar imaging from Venera-15, 16 and especially from the Magellan orbiter revealed practically the whole surface of the planet. Veneras 13 and 14 made first in situ analysis of the surface soil.

In spite of this extensive past exploration of Venus, many fundamental scientific questions remain. The Venus Surface Sample Return (VSSR) mission was designed to address many of these questions by returning a rock sample to the Earth for detailed analysis. However, the VSSR mission requires a number of new technologies that entail significant risk in the absence of prior flight validation. Therefore, we propose a lower-cost precursor mission that will provide validation of the key technologies and return useful science data on those parts of the atmosphere poorly covered by the past missions.

More accurate knowledge of the atmosphere is need from the surface to 60-65 km, which is the environment where VSSR mission will operate. There is no accurate data on the vertical structure of the lowest 12 km of the atmosphere. The stratosphere, with exception of the probes' accelerometer data, has been essentially unexplored with *in situ* measurements. It is also unknown if any significant changes in the structure and circulation of the atmosphere have occurred since the last Vega mission in 1985. The suggested precursor mission will address these and other fundamental questions on physics of the atmosphere, including the nature, pattern and evolution of the atmospheric circulation in the troposphere and stratosphere, the nature and distribution of the UV-absorber, and the structure and composition of the stratospheric clouds.

2. Venus Atmosphere Environment

The vertical structure of the atmosphere of Venus, as measured by entry probes and orbiters [(2)], is shown in Fig.1. The middle atmosphere – from 12 to 55 km is covered with the most accurate data. The detailed structure of the lower atmosphere (0 to 12 km) is still unknown; Venera and Vega-2 pressure sensors were not accurate enough, and sensors of Pioneer Venus probes ceased to function below 12 km.

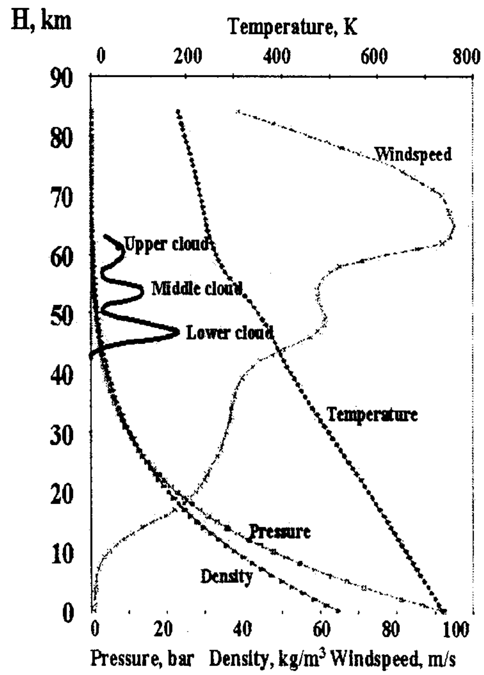

Figure 1. Vertical structure of atmosphere of Venus

There is significant lack of high-resolution data on the atmospheric structure above 55-58 km since the descent probes passed rapidly through this region. Most of data was obtained from remote measurements (radio-occultation, IR-radiometers and IR-spectrometers) and from accelerometers on descent probes.

Must be removed

One of the most enigmatic features of Venus is the atmospheric circulation. Prompted by Earth-based UV observations of high-altitude cloud structure and unambiguously discovered by Venera 8 measurements, the super-rotation phenomena remains unexplained. Vertical structure of winds above 55 to 58 km is poorly known because of the above-mentioned lack of resolution of probe data. Altitude of winds derived from UV-clouds motions is also unknown.

Clouds cover the entire surface of Venus, extending tens kilometers above an approximate base of 47-48 km [3]. Of the three major cloud layers – low, middle and upper – the upper was less covered with direct measurements. There are still uncertainties in cloud composition and in the nature of the absorber responsible for the appearance of Venus in the ultra-violet.

No direct measurements were conducted in polar areas, where a very different thermal pattern was observed by the Pioneer Venus IR-radiometer.

3. Venus Sample Return Mission (VSSR)

The 3000 kg VSSR spacecraft would be launched on a Delta IV medium vehicle. After about ~~of~~ four months of flight to Venus, the spacecraft performs an aerocapture maneuver with an inflatable decelerator, also known as a ballute. Plane change maneuvers and aerobraking bring the spacecraft to a 300-km circular equatorial orbit. At the proper time a small pulse deorbits the entry vehicle with the lander while the orbiter continues its active life. The lander enters using another ballute and descends to the surface in approximately 1-1.5 hours. Terminal velocity in the dense lower atmosphere is less than 10 m/s, and no parachute may need to effect a safe landing.

Shortly after landing the ultra-sonic drill takes a sample and a sample transfer mechanism loads the sample into the return canister located on top of the 470-kg solid-motor rocket called Venus Ascent Vehicle (VAV). Due to huge atmospheric drag losses it is impractical to launch the VAV from the surface of Venus. Instead, the VAV is lifted by a balloon to an altitude of 60 km or more (equivalent to altitude ~9 km on the Earth) where the VAV is launched for rendezvous with the orbiter. After the rendezvous and canister transfer to the orbiter, the orbiter propulsively escapes from Venusian orbit and returns to Earth.. Collection of the sample canister would follow the scheme developed for the Mars Sample Return mission., either direct entry to the Utah test range or placement into low Earth orbit for retrieval by the Space Shuttle.

VSSR has a number of new technologies that are critical for the mission:

1. Ballute – inflatable aerodynamic decelerator to be used for aerocapture of the spacecraft and for deceleration of the lander. Though the first studies were made 30-40 years ago the first test of entry decelerator has been performed in early 2000 by the Russians [4] . The detailed analysis of experiments has not yet published; however, it seems likely that the Russian concept will require significant modification for use in aerocapture applications.
2. Thermal protection of the VAV – the solid fuel in the VAV should be kept cool during the mission. Approximately 5 hours will be spent in atmospheric temperatures above 200°C. The proposed VSSR concept of thermal insulation needs to be tested for this purpose.
3. High-temperature balloon – balloon material and seaming technology should be developed and tested that would tolerate the environment after balloon inflation and during ascent. The temperature range from 460°C to -20°C with presence of concentrated sulfuric acid droplets.
4. Thermal protection of inflation tanks – the balloon will require 70 kg of helium to be stored in tanks and delivered to the surface of Venus. Initial tank pressure is 1000 bars and the tanks should be kept below 80°C up to start of the balloon inflation.
5. Balloon inflation and launch from the surface – currently only small latex balloons are launched automatically. Remote deployment, inflation and launch of the considerable size balloons (1000 m^3) needs validation also.

4. VSSR Precursor Mission Concept

The entry vehicle will be delivered to Venus by a spacecraft launched by Delta 7325 class launch vehicle. One to two months prior to arrival the entry vehicle will be targeted to the desired location at Venus and the cruise stage will perform an avoidance maneuver to fly-by the planet. The fly-by will be used to provide a reference source for Differential Very Long Base Interferometry (DVLBI) measurements for velocity of the balloons [5].

The entry vehicle will house two probes: Probe-1 with the stratospheric zero-pressure balloon with deployment and inflation system, and the instrumented gondola, Probe-2 with the lander, gondola, lifting balloon and gas tanks.

The mission sequence is shown in Fig. 2 a, b. A small ballute will be deployed and inflated prior to insertion into the atmosphere. The ballute will be used as auxiliary decelerator in addition to the aeroshell. The recorded deceleration during the entry will help to validate the ballute performance.

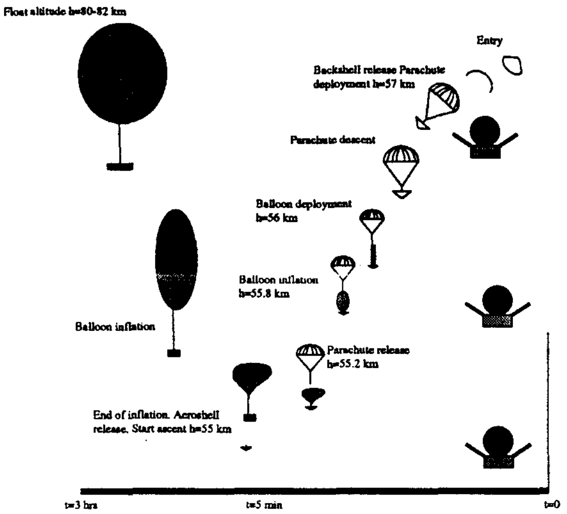

Figure 2a. Entry and Probe-1 flight profile

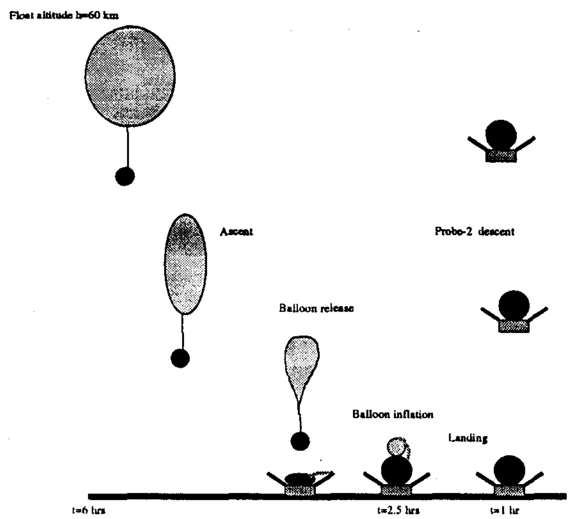

Figure 2b. Probe-2 flight profile

At an altitude of 58 to 56 km, the back shell will be ejected and two probes will be separated: a parachute will decelerate Probe-1 whereas Probe-2 will continue a free descent. When Probe-1 reaches terminal velocity, the balloon container opens and the balloon deploys with the inflation system suspended from the bottom fitting. The inflation process lasts 30 to 60 s. Ten seconds prior to completing inflation, the parachute separates from the balloon with inflation system and gondola still suspended. Five to ten seconds after completion of inflation, an adequate distance between the parachute and the balloon will be achieved and the inflation system will be dropped. The balloon then starts to ascend, with the gondola hanging below the bottom fitting. With an expected rate of ascent of 3 to 5 m/s the balloon will reach its ceiling of 80 to 82 km in 1.5-3 hours.

During the ascent data will be transmitted directly to the DSN via one-way X-band link and low-gain antenna. The antenna pattern can be matched to the expected geometry and can take advantage of an almost ideal vertical orientation of the flight system during ascent.

Probe-2 will land on the surface in 1.5 hrs; even without a parachute landing velocity would be less than 5 m/s and a simple crushable flatbed or torus could be used to absorb the energy of landing (this type of landing device was used successfully by six Venera and two Vega landers). Selecting the landing site at the Venus plains will reduce landing risk. After 1.5 hrs of stay on the surface, the lifting balloon container will be opened and the balloon will start to inflate through an inflation pipe attached to the top fitting. In 1-2 min inflation will be completed and the balloon with the gondola will be released from the lander. In 4 hrs the system will ascend to 60 km and will stay there until it will loose its free lift due to updraft and downdraft atmospheric motions. During all phases data will be transmitted to the DSN over S-band direct-to-Earth (DTE) link.

5. Probe-1: Mesospheric Balloon

The concept was described in [6]. The balloon has a traditional zero-pressure natural shape design with modifications for aerial deployment and inflation. Due to the relatively benign temperatures (20 to 30 C) at altitude of deployment , the balloon can be made of polyethylene. Resistance to sulfuric acid breakdown and low density makes polyethylene a preferable choice for the Venus cloud environment. Fig.3 shows balloon diameter and mass for 6.25 μm polyethylene balloon as a function of payload mass.

To sustain loads during aerial deployment, some of the balloon seams could be reinforced with Spectra fibers. The ripstitch shock absorbers are key elements of the deployment system to effectively limit

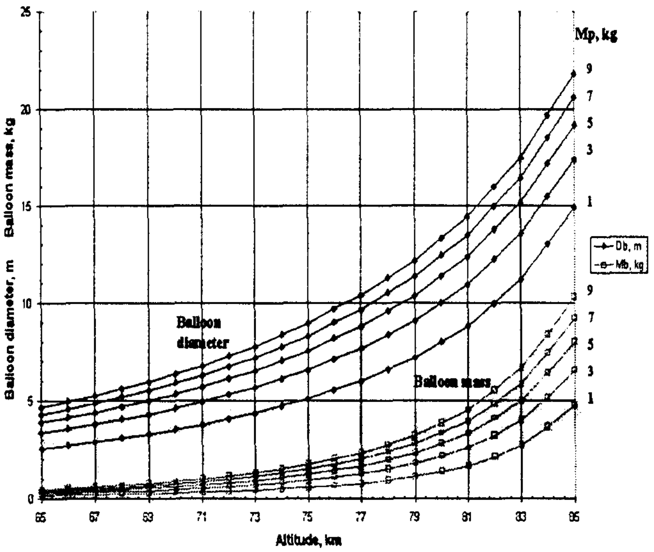

Figure 3. Balloon diameter and mass as functions of ceiling altitude and mass of payload

deployment loads. Other elements of the deployment system are pyro cable-cutters, the balloon container and a system of tethers that connect all parts.

6. PROBE-2: LANDER AND LIFT BALLOON

Lander. The lander component of this mission is intended to collect atmospheric data below 12 km and to test two critical VSSR technologies: thermal insulation and balloon deployment and inflation from the ground. Preliminary design suggests that these objectives can be met with a relatively small, 45 kg landed vehicle. Table 1 shows a mass breakdown by component. There are four main subsystems: lander structure, ascent balloon, helium gas supply and instrumented gondola. Each will now be described in more detail.

The Venusian atmosphere is sufficiently dense (64 kg/m^3 at the surface) that impact velocities of less than 5 m/s are possible without the use of parachutes on such a small lander. Therefore, we propose here to use a simple pallet-type lander with a crushable base to absorb the energy of impact.

This approach should be suitable for landing in the large, flat plains on Venus that contain minimal slopes or rock hazards. It was used on eight previous Russian Venus landers.

Table 1: Lander Mass List

Component	Mass (kg)
Lander structure	10.0
Gondola payload and pressure vessel	8.5
Gondola external insulation and PCM	7.0
Balloon	3.0
Balloon container, insulation, PCM	6.0
He gas	1.5
He gas tank and plumbing	4.0
He tank insulation, PCM	5.0
Total	45.0

The balloon, gondola and helium gas supply subsystems all require thermal insulation to limit the peak temperature experienced during the mission. We have estimated heating loads using a similar altitude vs time profile as was derived for the VSSR mission: 1.5 hour descent after ejection from the aeroshell, 1.5 hours on the surface, and 4 hours ascent to 60+ km.

The same 4-part ***thermal insulation*** strategy is proposed for all three subsystems. This is schematically illustrated in Fig. 4 using the helium storage tank as an example. Part 1 is a 5 cm thick porous insulation blanket wrapped around the component. High temperature Microtherm blankets [7] would appear to be suitable for this purpose, providing an effective thermal conductivity in air of only 0.03 W/m-K at 400 °C. Note that without a heavy pressure vessel to protect it, this insulation will fill up with CO_2 gas during the descent to the surface. Part 2 of the thermal protection system is a heat sink comprised of a high heat of fusion phase change material (PCM) like water (0 °C, 333 kJ/kg) or lithium nitrate trihydrate (30 °C, 296 kJ/kg). This heat sink will be used to absorb heat coming through the insulation and to cool the CO_2 gas filling up the pores of the insulation. The inlet tube and CO_2 gas – PCM heat exchanger comprise Part 3 of the thermal protection system. Finally, Part 4 is a Teflon membrane that provides a gas impermeable skin for the insulation blanket and forces CO_2 to enter the insulation void by going through the PCM heat exchanger.

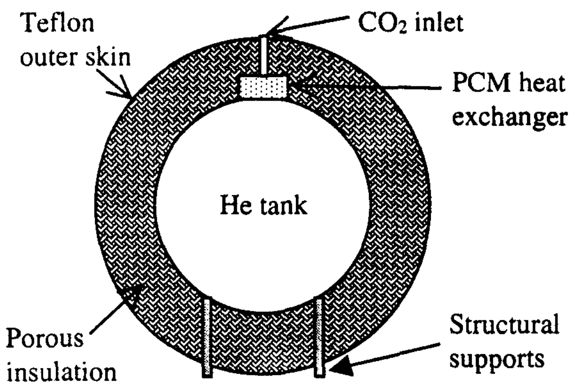

Figure 4. Insulation Schematic For Helium Tank

The gondola consists of a 30 cm diameter Ti-6Al-4V pressure vessel that contains the flight electronics, transmitter, batteries, temperature and pressure sensors. These are the only landed components that need to be protected from the 90 atmosphere surface pressure at Venus. An external blanket plus 3 kg of PCM will keep the inside gondola temperature roughly constant during the descent and surface stay. However, since this protection is discarded at the moment of ascent, additional insulation and phase change material must be provided inside the gondola to protect it during the 4 hour ascent. Since the pressure vessel keeps out the CO_2, we can use Xenon gas in the gondola to provide superior insulation performance [(8]. As seen in Table 1, the gondola masses 8.5 kg, not including the external insulation and PCM.

A 4 m diameter ***natural shape zero-pressure balloon*** is required to lift the 8.5 kg gondola to 60 km at Venus. This balloon will mass 2.1 kg based on the 60 g/m^2 Teflon coated PBO cloth material described elsewhere in the next section. The balloon must be filled with 1.5 kg of helium gas to provide 20% free lift, enough to get the gondola to 60 km in approximately 4 hours. Note that the balloon will be stored in a container prior to surface deployment where the balloon temperature should not exceed 300 °C as per the material specification. This container will therefore be protected by the standard insulation blanket and PCM arrangement described above to achieve this temperature requirement.

The 1.5 kg of helium gas will be stored in a carbon fiber wound composite pressure vessel with a nominal pressure of 1000 atm. Another 5 cm thick insulation blanket along with 2 kg of PCM will serve to keep the helium tank below 80°C. A simple orifice will be used to set the flow rate of helium gas into the balloon such that inflation is complete in approximately 1 minute.

Deployment, inflation and launch of the lift balloon. The lift balloon will be packed in a storage container on top of the lander. If deployed, the 4-m diameter balloon will have a length of 6.5 m. To minimize launch equipment and reduce risk the balloon will be inflated through a 1.5 m pipe attached to the top of the balloon. Due to ambient pressure and density difference, on the surface the balloon volume with all 1.5 kg helium inside will be about 100 times smaller than at 60 km altitude and diameter of the inflated part would be less than 1 m. According to Venera 9, 10 data, winds the surface do not exceed 1-1.5 m/s and the small size of balloon makes it manageable during the launch. This inflated part of the balloon (bubble) will be attached to the lander until the launch. At the launch the gondola will be disconnected from the lander's structure and the balloon will be released. A ripstitch shock absorber will be used to mitigate the shock load when the gondola will be lifted from the lander. The balloon with the gondola will reach 60 km in roughly 4 hours.

7. CANDIDATE MATERIALS FOR THE LIFT BALLOON

In order to meet the harsh environment of Venusian atmosphere and surface, several candidate materials have been considered[(9,10)]: polybenzoxazole (PBO), polyimidobenzoxazole (PIBO), polyfluoroalkoxy (PFA) and polytetrafluoroethylene (PTFE) films, PBO and carbon fibers, metal foils such as nickel and titanium, and various composites thereof.

The selection of the current balloon envelope material concept is based on the assumption that while on the surface (during Venus surface sample acquisition) the balloon envelope will be kept at a temperature less than 300°C. Subsequent balloon deployment, inflation, and ascent to lower than 400°C altitude will take less than 60 minutes.

The use of PBO as the primary balloon material is attractive due to its good thermomechanical properties[(9,10)]. As seen in Figure 5, tensile testing of PBO film at elevated temperatures shows a retention of up to 14% of its room temperature strength at 600°C and over 37% at 450°C.

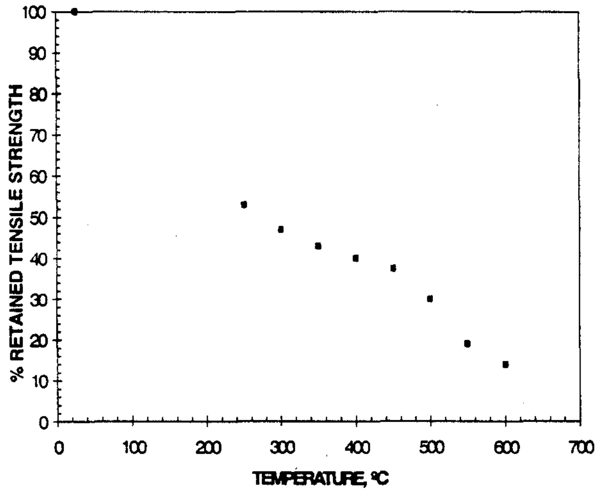

Figure 5. Retained Tensile Strength of PBO Film at High Temperature

Tensile testing of PBO fiber at 600°C indicates a similar temperature dependence as that of the film. This data agrees with PBO fiber data obtained by the manufacturer of Zylon® fiber, Toyobo Corp., Japan. On the other hand, due to PBO's incompatibility with the sulfuric acid environment, coating materials would be needed for the protection of this high temperature polymer.

Since no single film has all necessary properties, several composite materials have been considered. For instance, the use of PBO or carbon fiber in a scrim network would greatly enhance the strength of the balloon without exceeding weight limitations. A non-load bearing fluoropolymer coating could then be applied to the scrim to complete the balloon composite material.

The stability of fluoropolymers toward sulfuric acid has been evaluated[10] and several fluoropolymer composites have been proposed. The thermal stability of some of the commercially available fluoropolymer films is shown in Figure 6 and Figure 7. Preliminary tests indicate that thin Teflon (PTFE) film is practically inert and impermeable to concentrated sulfuric acid.

In summary, the proposed candidate film will be composed of PBO fabric, coated with PTFE resin on one (outside) or both sides. In addition, the PTFE layer will be metallized or coated with MoS_2 or graphite powder to eliminate the surface tackiness of the resin at these temperatures. Increasing strength and better tear resistance would result from such a composite design. Furthermore, such composites would decrease the technological development necessary for balloon fabrication, as both PBO and carbon scrim fibers are commercially available. The use of fabric scrim would also significantly simplify the seaming technology which otherwise will require the development of high temperature adhesives. However, as a preliminary concept design, no data exists on such a composite. Hence, extensive characterization studies would undoubtedly be required.

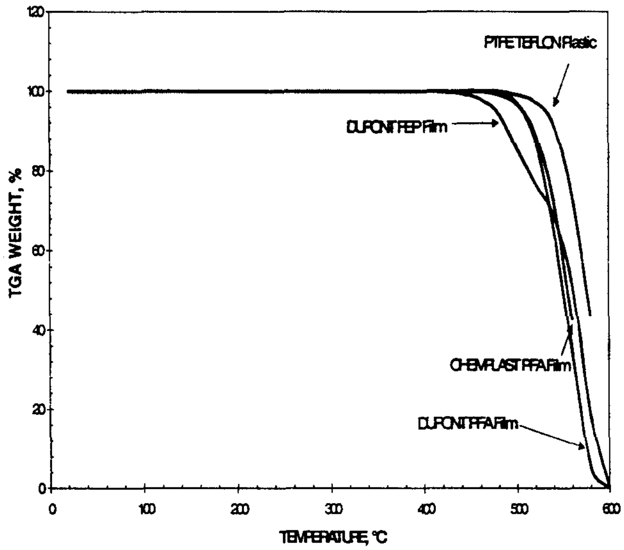

Figure 6. Weight Loss of Fluoropolymers versus Temperature

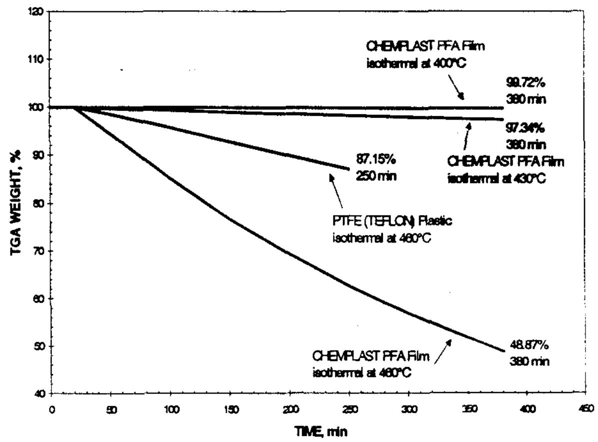

Figure 7. Isothermal Weight Loss of Fluoropolymers

8. Measurements and Communications

Instruments. On Probe-1 the basic instruments may include pressure and temperature sensors (for measurements of thermal structure) and nephelometer (to study the vertical structure of clouds). No special requirements are imposed on the sensors (especially on the night-side) since the balloon ascends relatively slowly. The temperature sensor should be protected from possible deposition of sulfuric acid. Other instruments may include radiometer to measure thermal fluxes and one-axis accelerometer to record the turbulence. Attempts to measure atmospheric composition, and especially the nature of the UV-absorber, seem the most challenging and it is unclear if it is feasible to do within the spirit of a low-cost precursor mission.

On Probe-2 science measurements will be concentrated on getting accurate data on vertical structure of the lower atmosphere of Venus and may include pressure and temperature sensors only. A set of engineering temperature sensors will be put at locations that will characterize thermal protection performance and thereby validate the design. The control points will include inner and outer walls of the gondola, inside the thermal insulation, walls of helium tank and balloon envelope.

Probe-1 will use an X-band transmitter with 5 W RF power output. With an omni-directional antenna (gain~0dB), the system can achieve data rates of 10 to 20-bits/sec at distances of 100 to 150 million kilometers (which are typical for Venus missions). This data rate is compatible with the low ascent rate of the balloon, approximately 5-m/s, so that a 5 sec sampling period will provide data every 25 m, which is essentially a continuous coverage.

The slowly-ascending balloon is a good tracer of wind since the horizontal velocity of balloon is equal to local wind velocity. The DVLBI tracking is the most accurate and adequate method to measure drift of the balloon and correspondingly vertical profile of wind. DVLBI effectively measures angular motion of the balloon relative to a reference source which position is known. This method was used successfully to determine winds with Pioneer Venus probes and VEGA balloons. With the cruise stage during fly-by as the reference source, the expected accuracy of wind measurements will be better than 0.3 m/s.

A similar transmitter operating at S-band will be used with Probe-2. S-band is needed because carbon dioxide at high pressures in the lower atmosphere of Venus absorbs strongly X-band radiation. Lithium batteries will be the primary power source for this short-duration mission. Continuous transmission with a total DC power consumption of 20 W over 3 hours for Probe-1 and 6 hours for Probe-2 would require 300 g and 600 g of batteries respectively. An ultra-stable oscillator will make it possible to measure winds with high vertical resolution using tracking of both balloons with Differential Very-Long Base Interferometry method.

9. Summary

The proposed concept of a VSSR precursor is a relatively low-cost mission with high both scientific and technological return providing accurate measurements of the Venus atmosphere from the surface to 80-82 km and validating key technologies that will be need for much more expensive and much more visible Venus Surface Sample Return Mission.

10. Acknowledgements

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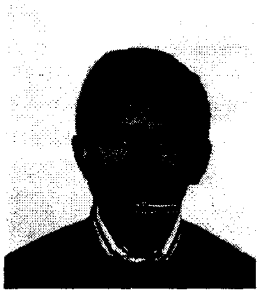
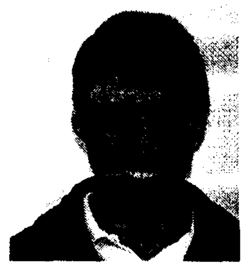


Viktor V. Kerzhanovich received his B.S. in physics from Moscow State University, Candidate of Science degree and Doctor of Science in physics from the Space Research Institute of the Soviet Academy of Sciences, Moscow. He took part in atmospheric experiments, tracking and data acquisition on all Soviet deep space probes to Venus and Mars, including Venera 4-16, the VEGA, and Phobos. In 1997 he joined the Jet Propulsion Laboratory/ California Institute of Technology as a Senior Member of Technical Staff. Since then, his efforts have been concentrated on development of aerobot technology for planetary applications. His technical interests include scientific ballooning, communication, tracking and navigation. Dr. Kerzhanovich has published over 100 papers on technology applications, mission concepts and planetary studies. He is a member of AIAA Technical Committee on Balloon Technology.



Jeffery L. Hall received his B. A. Sc. (Hons.) degree in Engineering Science from the University of Toronto in 1984, and M. S. and Ph. D. degrees in Aeronautics from the California Institute of Technology in 1985 and 1991 respectively. He joined the Jet Propulsion Laboratory in 1997 where he has worked on a variety of technology development and mission design projects including planetary balloons, Venus atmosphere probes and landers, aerocapture vehicles and cryogenic refrigeration. Dr. Hall is a Senior Member of the AIAA.

Andre H. Yavrouian received his M.S. in Organic Chemistry and Polymers from Sofia State University, Sofia, Bulgaria. In 1977 he joined JPL and since 1990 has been Group Supervisor of the Analytical Chemistry & Material Development Group. His recent involvement include evaluation, characterization, qualification and testing of materials for planetary balloons, ballutes and inflatable planetary rovers and development of sterilization concepts for Mars Sample Return. Flight project involvement includes area of propellants chemistry, materials selection, materials compatibility and testing for Cassini, Wide Field Planetary Camera, Mars Observer, Galileo and other spacecrafts.

Past years involvement includes synthesis and development of carbons for sorption cooling, polyurethanes for electronic part encapsulation, artificial blood substitutes, fuel additives to suppress post-crash aircraft fires, polymerizable UV absorbers for solar cell encapsulation and others. List of publication includes over 80 papers, scientific reports and patents.